Module 1 - Situation: Body Ambient Bondgraph Model Using Heat Flux Transducer

Introduction

There are numerous occupational and leisure tasks for which the participants are at risk of heat stress related illness. Current practices for protection against heat stress illness are limited to education and self evaluation. Independent monitoring by means of sensors has not been adopted by industry due to reasons of impracticality. Direct measurement of body core temperatures is impractical for the majority of occupational and leisure tasks.

The model presented in this paper shows all elements of heat transfer, providing a complete systematic view of antagonistic conditions and the human body. This paper describes how heat stress illness can be prevented by monitoring the body thermoregulatory response and predicting catastrophic failure. This is evident in measuring the heat transfer to and from the body, and comparing this data to heat transfer during normal operation.

Body Thermal Regulation Mechanisms and Antagonistic Conditions

The human body at all times will strive to maintain a core temperature at approximately 37 ± 0.6 ºC. The core temperature is defined as the temperature of the arterial blood at the aorta. The high specific energy of blood and low thermal impedance to internal organs maintain critical organs at a temperature very similar.

Focusing this paper upon conditions where the body is at risk to over heating, we can describe three primary mechanisms of heat transfer: radiation, convection and conduction, and evaporation.

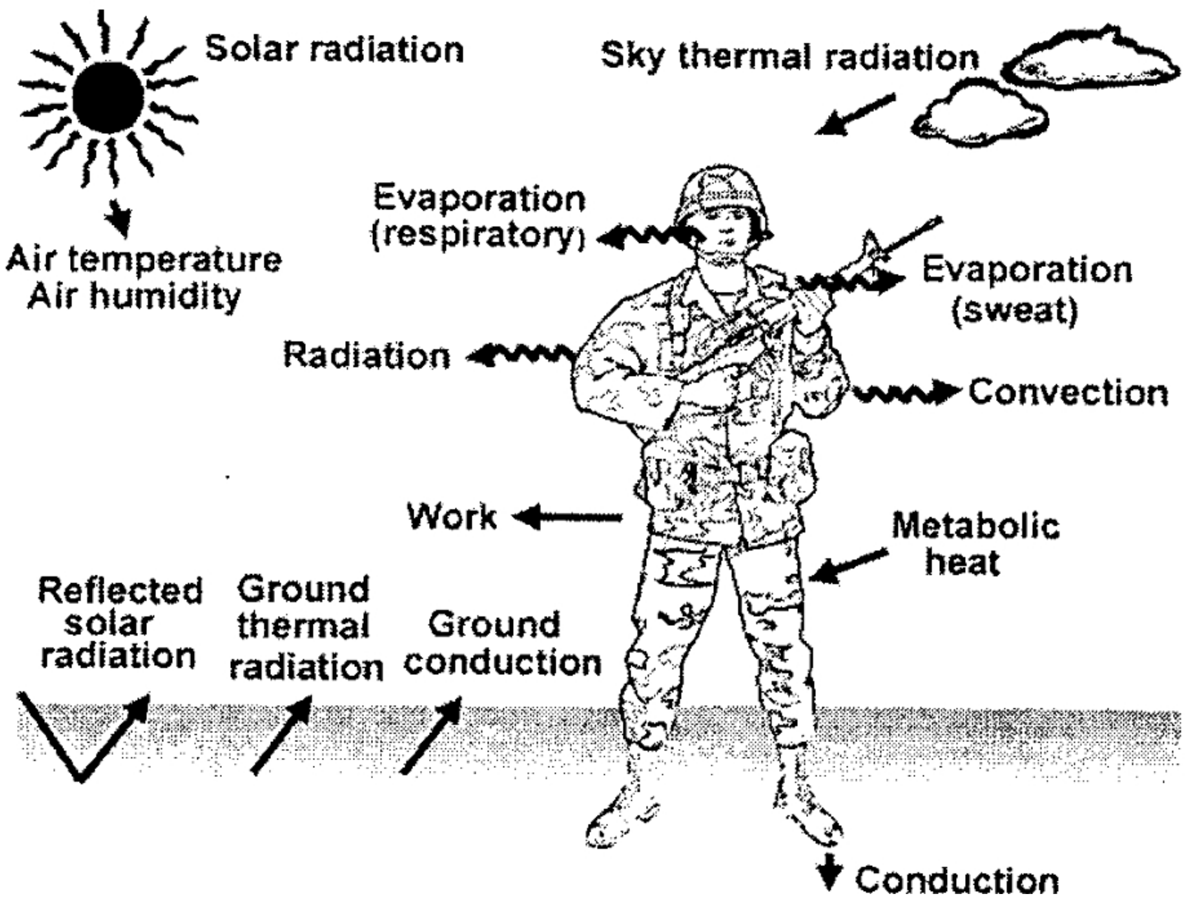
Heat will radiate to or from the body based on the temperature differential between the skin and external objects. Air temperature contributes only a

small factor in heat radiation, as air is a poor radiator. If the body is in direct or reflected path of the sun's rays, the body will absorb heat.

Heat will transfer to or from an object in contact with the skin. In the case where the object is air, this is known as convection, be it natural (still air) or forced (moving air). In the case the object is something other than air, it is conductive heat transfer. Conductive heat transfer is not typical of most environments where heat illness is a risk.

In evaporation, sweat is diffused across the skin and condenses on of the skin. Heat is transferred from the skin to ambient as the sweat changes phase from liquid to gas. This is the most effective heat transfer mechanism of the human body. In environments where the relative humidity is high, sweat will not evaporate, this mechanism provides no relief. An average person will not tolerate temperatures above 33ºC, even at rest, without the ability to dissipate heat through evaporation.

Figure 1: Modes of Heat Generation and Transfer for the Human Body



The primary response of the body to an increased core temperature is to increase blood flow to extremities by dilating the capillaries of the blood system, effectively using parts of the body as a thermal sink. Mass flow can further be improved by increasing the heart rate. As sweat is secreted to the skin, the sweat evaporates and energy is further dissipated through phase change.

Heat Stress and Risks

Heat stress illness effects can be either acute, such as heat stroke, heat exhaustion, heat cramps, fainting, and decline of performance; or chronic, such as loss of ability to tolerate heat, hypertension, heart muscle damage, reduced libido and impotence.

Figure 2: Spectrum of Heat Stress Illness

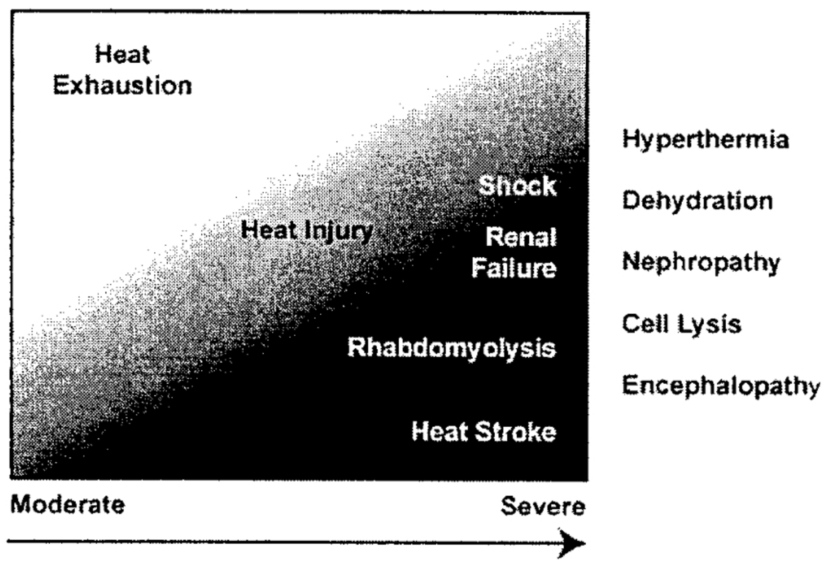


Figure 4-1. Spectrum of heat casualties, encompassing the continuum of mild (heat exhaustion) to severe (heat stroke) with associated categories of physiologic dysfunction.

Description of Occupational and Leisure Tasks

Aerobic athletes, such as the example of a runner during a marathon, will generate heat in a consistent manner for an extended period of time. The environment can be variably providing either beneficial or antagonistic conditions. Clothing and equipment do not generally impede the dissipation of heat.

Anaerobic athletes, such as the case of a football player, generate heat in short durations. The effects of this heat generation can be cumulative if periods of rest are not long enough to decrease body temperature, or if periods of exercise are long enough to exhaust reserves of body fluids. Environmental conditions are variably beneficial or antagonistic. Clothing and equipment can impede heat dissipation to the environment.

Some occupational tasks generate heat in short durations, but over extended periods of work. Examples include roofers, construction workers, or farmers. Antagonistic conditions are common. Clothing and safety equipment generally provide some impediment to heat dissipation.

Environmental conditions can extreme in occupations such as firefighters or other workers in high heat environments. Protective equipment is designed as a thermal insulator, which also serves to prevent the body from dissipating heat.

Current Practices for Protection Against Heat Stress

The current approach to protection against thermal stress involves worker education. Employees are given information on how antagonistic conditions exacerbate overheating risks and how to recognize the early signs of heat stress illness.

Figure 3: Sample Educational Chart for Self Monitoring Against Heat Stress Illness

Warning signs and symptoms of possible heat illness and injury

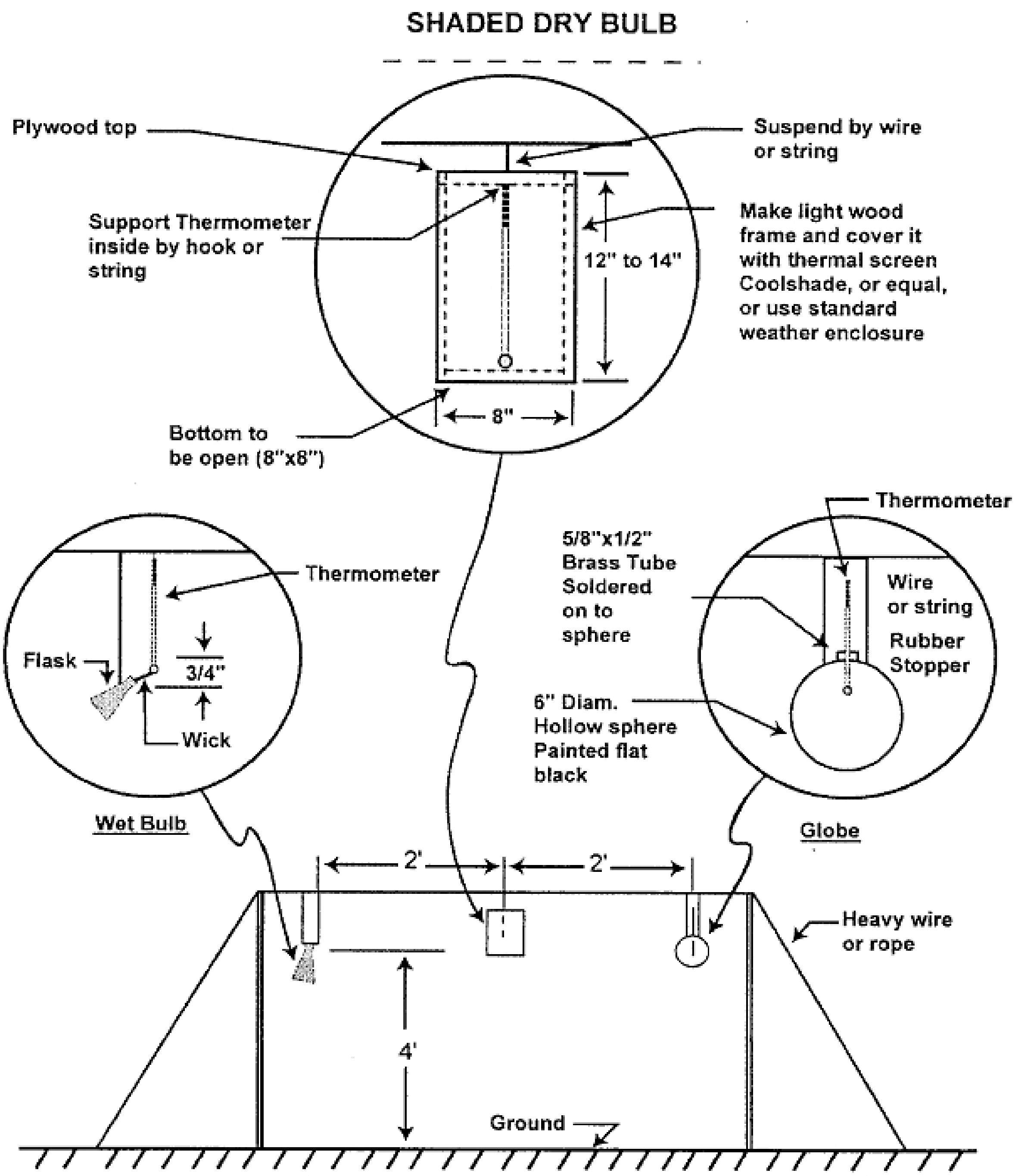
More Common Signs/Symptoms*	Immediate Actions
• Dizziness • Headache • Nausea • Unsteady walk • Weakness • Muscle cramps • Fatigue • Chills	• Remove from training • Allow casualty to rest in shade and fan and spray with water • Loosen clothing • Take sips of water • While doing the above, call for medic evaluation of the soldier. (Medic will monitor temperature and check for mental confusion.) • If no medic is available, call for ambulance or medical evacuation.
Serious Signs/Symptoms	**Immediately Call Medical Evacuation or Ambulance For Emergent Transport While Doing the Following:**
• Hot body, high temperature • Confusion/disorientation (mental status assessment) • Vomiting • Involuntary bowel movement • Convulsions • Weak or rapid pulse • Agitation • Unresponsiveness, coma	• Laying person down in shade with feet elevated until medical evacuation or ambulance arrives. • Undressing as much as possible. • Pouring cool water over the person and fanning • Cool by best means available (water immersion or ice sheets/packs). • Giving <u>*sips*</u> of water if conscious. • Monitoring airway and breathing.

*With any of the signs or symptoms, immediately call for medical evaluation by a medic.

The Wet Bulb Globe Temperature (WBGT) index is considered the authoritative standard in providing employees usable information in quantifying the severity of antagonistic conditions. It is derived by taking measurements with three devices that separate heat flow components all effects save for wind speed, all effects, and ambient temperature. These measurements are then combined by means of a weighted average to the WBGT.

Unfortunately, while the WGBT method is accurate and reliable, it is also requires expensive equipment with high maintenance requirements. As such this method is impractical for small scale facilities, and such data is not even recorded at typical meteorological sites.

Figure 4: Dry and Wet Bulb Measurement Setup for WBGT Index Data



Alternate Practices

There are two established methods of reliably monitoring body core temperatures for a mobile person. These include probes inserted within the esophagus, and alternately the rectum. Both are uncomfortable, and impractical for periods in excess of 24 hours.

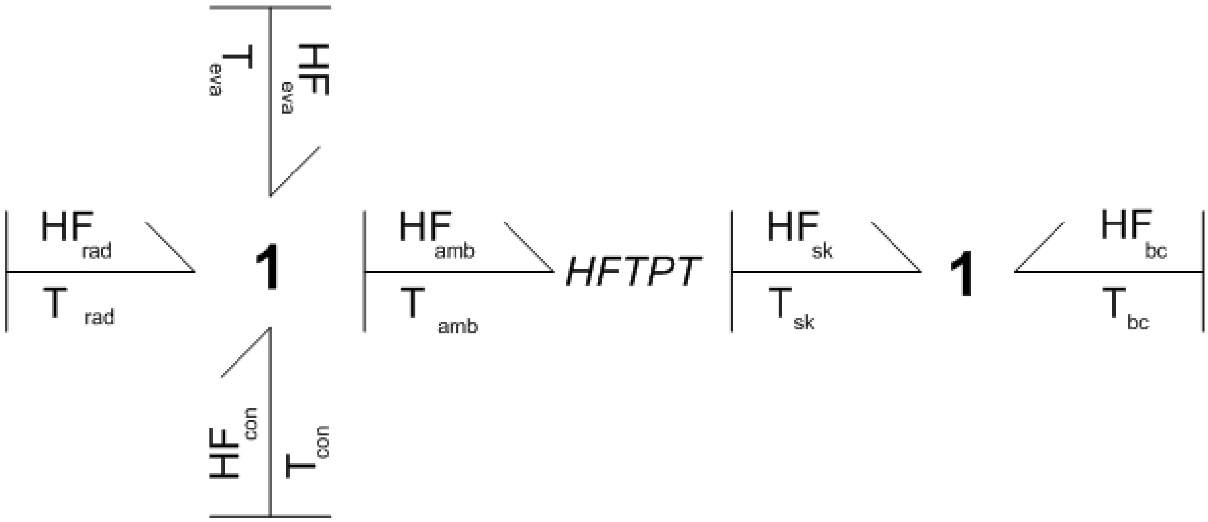
A third device still under development and involves a wireless device which is ingested, providing persistent monitoring as it works it’s way through the digestive system over a period of 18 to 36 hours. Studies to date show the performance to be nearly as dependable as the established esophageal and rectal thermometers. Its primary drawbacks are that the devices are not reusable, and has not yet been widely accepted by the market.

Various devices have been developed which monitor skin temperature. Skin temperature itself is a poor estimate of core temperature due to the greatly variable impedances between core to skin, as well as skin to ambient. Some efforts couple skin temperature with other measured factors, such as heart rate, accelerometer data, and WBGT index information in an effort to arrive at a more accurate estimation. None of these efforts have proceeded past initial trials.

Bondgraph Model and Heat Flux Transducer

This paper proposes a bondgraph model for the understanding of the heat transfer mechanisms between the human body and ambient under various conditions. Individual contributions to body heat are shown as r-elements. A measurement device of a heat flux transducer is shown as a transformer element. The equation layer of the model can be tailored for various operating conditions, using either derived or empirical formulas to describe heat transfer.

Figure 5: Bond Graph Model of Heat Flow and Temperature of the Human Body



The model shows the same components of body-ambient heat transfer as are found in most occupation educational literature. The model further demonstrates causality and direction of power flow. The system equation layer provides the ability to mathematically quantify contributing elements of system heat transfer.

Results

This approach holds advantages over existing methods in that the person at risk is no longer responsible for their own protection, thereby removing certain conflicting interests in making a determination. The model presents total system data for the body and ambient environment.

Module 2 - Model: Body Ambient Bondgraph Model Using Heat Flux Transducer

Introduction

There are numerous occupational and leisure tasks for which the participants are at risk of heat stress related illness. Existing practices for protection against heat stress are limited to education of antagonistic conditions.

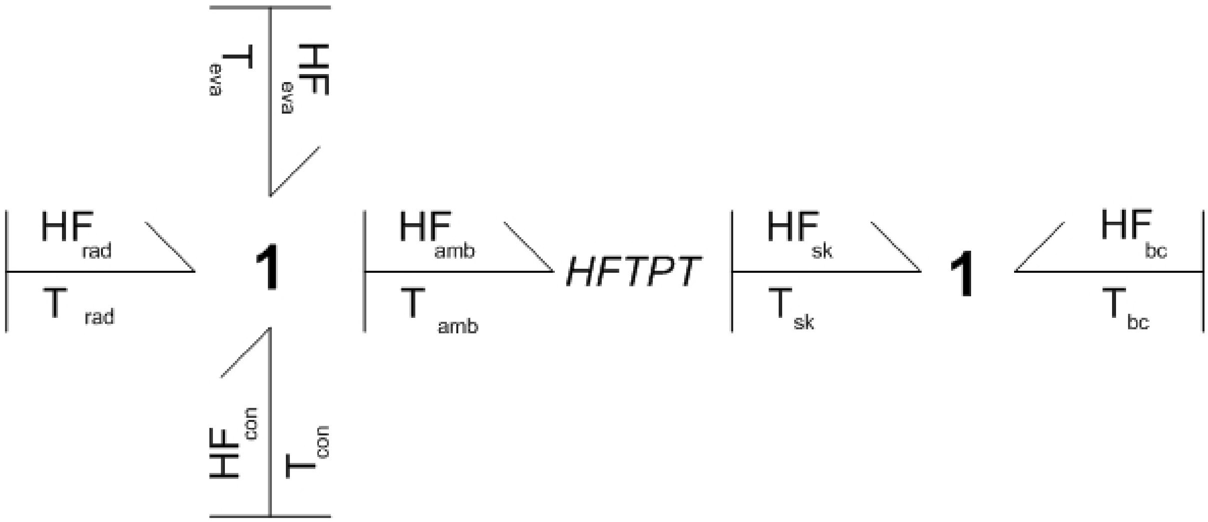
Education and self monitoring has the drawbacks in that any person tasked in making a qualitative judgment has motivating factors against protecting themselves. Methods for persistent monitoring exist but have not been adopted by industry for several factors. Measurement of body core temperature is impractical for almost all occupations. Measurement of skin temperature is not dependable as it is not a leading indicator of heat stress illness.

The bondgraph model provides a complete system view of the contributors to heat stress, and the equation layer of the model can be tailored for various operating conditions, using either derived or empirical formulas to describe heat transfer. This paper describes a model tool such that a heat flux transducer can provide a leading indicator of heat stress illness for a variety of tasks.

Model

A Bondgraph model is a graphical technique to describe energy flow in and amongst physical systems. Presented below is a Bondgraph model to illustrate the body-ambient heat exchange and how it would be measured using a heat flux transducer

Figure 1: Bond Graph Model of Heat Flow and Temperature of the Human Body



Where,

HF = Heat Flow

T = Temperature

Eva = Evaporation

Rad = Radiation

Con = Convection

Amb = Ambient

Sk = Skin

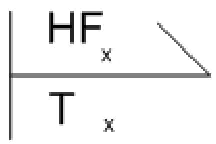
Bc = Body Core

For those new to Bondgraph models, the following explanation uses terminology specific to the model presented in this paper:

- Each element shows that there is a relationship between heat flow (HF) and temperature (T). To translate the above into generic bond graph terminology, heat flow is the bondgraph "flow" factor; temperature is the "effort" factor.

- The arrows illustrate the sign convention for direction of power flow. Power flow can be in either direction (either positive or negative)
- Strokes show causality. As shown in the system equations, heat flux is dependant upon temperature
- "R-Element": The resistor is a 1-port an element in which the heat flux and temperature variables at the single port are related by a static function

Figure 2: Symbol for an R-Element



The half arrow means that the T and HF is positive; where T represents temperature, and HF, represents heat flow. The constitutive relationship is that heat flow is a function of temperature.

- "Transformer": The bondgraphic transformer can represents the heat flux transducer used to measure heat flux, located on the ambient-to-body threshold on the skin. It conserves power and transmits the factors of power with proper scaling as defined by the transformer modulus.

In a departure from a standard Bondgraph transformer, the modulus for this project inserts an offset and slope to the modulus representative of the error in the measuring device.

Figure 3: Symbol for a Transformer

- The large nodes labeled “1” are called 1-junctions. They indicate a node where the heat flows sum to zero.
- Radiation, convection, and evaporation are heat transfer phenomenon affecting the ambient.

System Equations

From the Bondgraph model, system equations may be generated using a step by step procedure. For the explanation of this model, generic heat transfer equations will be show to demonstrate the basis of usage in fundamental thermodynamic theory. Depending on the application, these equations can be replaced with more sophisticated equations based on heat transfer theory, or one could utilize empirically derived equations from field data.

Observe elements contributing to the system and write down equations looking at causalities.

For natural convection,

$HF = h\Delta T$ [W/m^2]

h = convective thermal heat transfer coefficient

ΔT = temperature difference between surface (skin) and fluid (air)

For conduction,

$HF = k\Delta T/x$ [W/m^2]

k = thermal conductivity of the material [W/m·ºK]

ΔT = temperature difference between surface (skin) and fluid (air) [ºC]

x = material thickness [m]

For radiation,

$HF = \varepsilon(T) \cdot \sigma \cdot T^4$ [W/m²]

$\varepsilon(T)$ = correction factor, (emissivity correction factor times radiation spectrum formula)

σ = Stefan-Boltzmann constant, 5.670400×10^{-8} [$W \cdot m^{-2} \cdot K^{-4}$]

T = temperature [K]

For evaporation, heat transfer equations are very complex, and now shown here. They are characterized by an s-shaped curve relating heat flux to surface temperature differences, which is the same reliance on temperature that holds for all equations in this model.

For heat transfer from the body core to skin, equations are a combination of series convection, conduction, and radiation transfers at various boundaries.

$HF = h\Delta T + k\Delta T/x$ [W/m²]

Write down equations for junctions and two-port elements.

For heat flux transducer transformer-element,

HFamb*Tamb = HFsk*Tsk =>

HFamb = (Tsk/Tamb) * HFsk * (1 + D)

D = sensor introduced deviance

HFrad + HFeva + HFcon + HFamb = 0

Trad = Teva = Tcon = Tamb

HFsk + HFbc = 0

Tsk = Tbc

Replace variables until the right sides of the equations are expressed in terms of states and system parameters.

$$HFbc = (h\Delta T + k\Delta T/x + \varepsilon(T)\cdot \sigma \cdot T^4 - Hfeva)\cdot(Tsk/Tamb)\cdot(1+D)$$

More complex models can be solved using MATLAB or a variety of simulation tools designed specifically for Bondgraph models.

Measuring Device

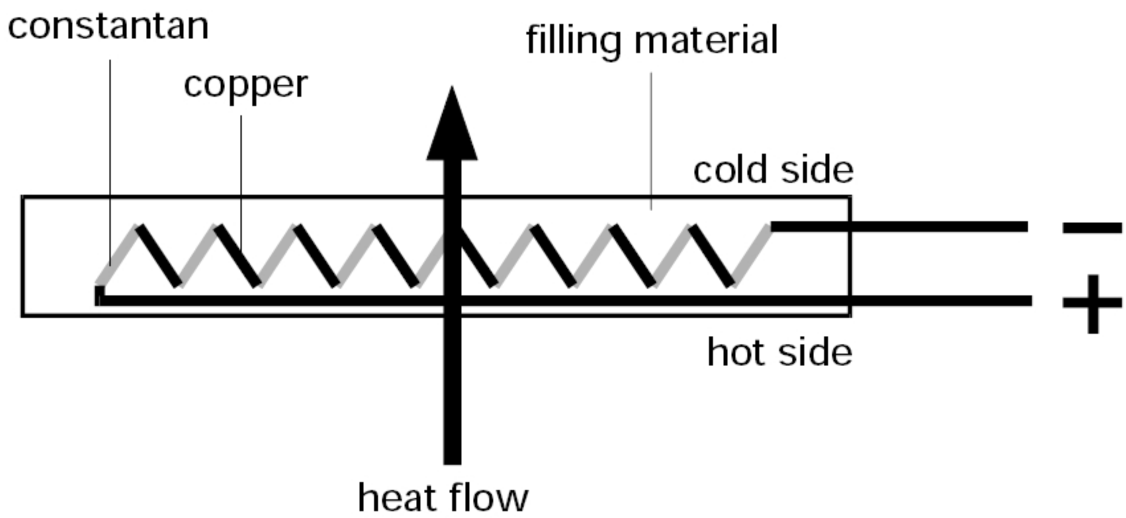
Heat Flux Sensor Defined

Heat flux is defined as the flow per a unit of area per unit of time. For this paper, we intend to utilize [W/m^2] (or Joule/second/meter^2).

The majority of heat flux transducers, including the one visualized for this project, are based as its beginning element the thermocouple. A thermocouple consists of a bond between to materials (typically copper and constantan) that behave differently to heat. This bond will form an impedance directly proportional to the temperature.

Numerous thermocouples connected in series create a thermopile, with the increased number of joints improving the signal. The thermopile is then embedded in a filling material which should provide a uniform distribution and a thermal impedance, at which point it may be considered a transducer. As heat flows from one side of the transducer to the, thermocouple joints create a voltage differential representing heat flux.

Figure 4: Heat Flux Transducer:



Sensor Related Error Sources

There are several sources of errors related to heat flux sensors, including dynamic effects, lateral fluxes, distortion/deflection, and additional data acquisition elements.

Dynamic effects errors are introduced when the heat fluxes change at a rate faster than the response time of the sensor. When specifying a sensor, it is therefore preferable to utilize sensors with a low mass. In the practice of a heat flux transducer for measuring heat flow to and from the human body, minimizing the size and mass of the sensor also improves the comfort and therefore utility of the device.

The heat flux of interested in body-ambient measurements is the flux perpendicular to the skin. If a sensor is sensitive to lateral fluxes, i.e. flux in the direction parallel to the surface of the skin that will introduce an error in the measurement. Lateral fluxes are minimized in the construction of sensors by maintaining uniformity in the filling material.

Distortion and deflection of heat flow occurs when the thermal impedance of the sensor varies significantly from the characteristics of the material being measured. Distortion is minimized by limiting the thermal impedance

of the filling material, increasing the size of the sensor surface area, or correcting for this error in sensor calibration. Deflection is minimized by adding a guard around the edge of the transducer, composed of the same material as the filling. Heat flow will be irregular in the guard region, but as it is not populated with thermocouples, heat flux measurements are not affected.

Self Calibrating Sensor

A self calibrating heat flux sensor is achieved by combining the heat flux transducer described above with a film heating element on one side. At regular intervals, the film heater is activated with a known generated heat flux, 50% of which will pass through the heat flux transducer. In the case of non-matching conductivities, a deviation occurs, which is then used to generate a new calibration factor to compensate for sensor errors.

Specification of Selected Device

With the above knowledge and some assumptions on how one would want to proceed with our theoretical application, one can generate a performance based specification for the design of a heat flux transducer:

Parameter	Specification and Justification
Sensitivity	125 $\mu V/(W/m^2)$
Range	-2000 to 2000 W/m^2
Response time	< 30s

Sensitive area	12.5cm² (.00125m²); Equivalent to a 5cm x 2.5cm patch
Thermal conductivity	0.209 W/m·K; equivalent to human epidermis
Guard area	0.5cm distance on each edge
Non stability	5% (maximum change in sensitivity per calendar year under calibration conditions)
Operating temperature	0 to 70ºC
Impedance	5 Ω
Accuracy	±5%
Self Calibration	Yes

Methodology

The methodology proposed for using the above sensor and model in the prevention of heat stress illness incorporates several steps. A heat flux transducer is affixed to the human body for the purpose of measuring heat flux during activity. Measurements are taken and the heat transfer is tracked over a period of time. System equations are utilized to develop an algorithm to recognize decrease of body thermoregulatory response and the onset of heat stress illness, particularly in comparison to the environmental conditions present. Finally, once normal thermoregulatory response has been characterized and monitoring algorithms have been developed, heat transfer is monitored for deviations, which may be accounted for by a decrease in the body thermoregulatory response.

Module 3 - Query/Answer/Significance: Body Ambient Bondgraph Model Using Heat Flux Transducer

Introduction

For the understanding of heat transfer between a human body and the ambient, a bondgraph model can provides a complete system view of the contributors to heat stress, and the equation layer of the model can be tailored for various operating conditions, using either derived or empirical formulas to describe heat transfer.

In this paper, we provide a query and answer on a theoretical situation to demonstrate how a heat flux transducer in conjunction with the body ambient bondgraph model would be used to monitor against the onset of heat stress illness.

Query

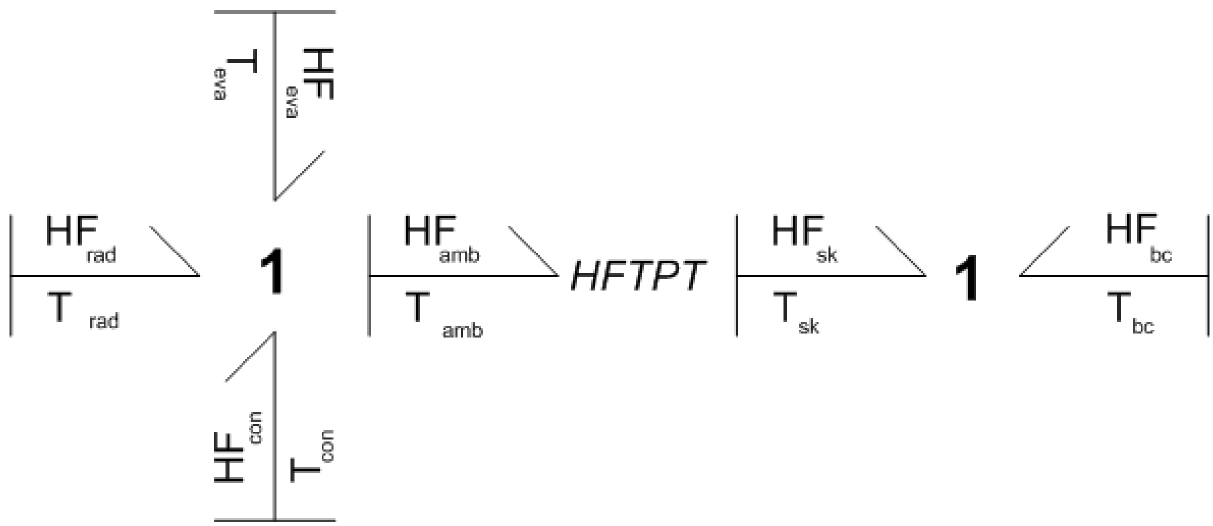
If a runner were to be instrumented with a heat flux transducer prior to running a marathon, how would the measured data be used to estimate the onset of heat stress illness, and what percentage of error needs to be figured into the measured data?

Answer

Model

A Bondgraph model is a graphical technique to describe energy flow in and amongst physical systems. Presented below is a Bondgraph model to illustrate the body-ambient heat exchange and how it would be measured using a heat flux transducer

Figure 1: Bond Graph Model of Heat Flow and Temperature of the Human Body



Where,

HF = Heat Flow

T = Temperature

Eva = Evaporation

Rad = Radiation

Con = Convection

Amb = Ambient

Sk = Skin

Bc = Body Core

Assumptions

- The runner is 6’ tall (183cm), 150lbs (68.2kg) and running at a steady pace to complete the marathon in a time of 3.9 hours (3.0m/s).
- The ambient temperature is 30ºC with a relative humidity of 60%; resulting in an apparent temperature of 35ºC.

- Still air environment, resulting in an apparent wind speed equal to running speed.

System Equations

The system equations layer of the model forms the basis for mathematical evaluation of system energy transfer. The equations presented below are empirically derived based on experimental field data.

- For approximate heat generated during running,

HFbc = (body mass[kg])*(running speed[m/s])[4J*s/m/kg]

- For heat loss due to evaporation,

HFeva = .312(Teva) + 25.2 [W/m^2]@ Tamb = 35ºC; 3.0m/s wind speed

- For heat transfer due to conduction and radiation,

HFrad = .5833(Trad) + 30.96 [W/m^2]@ Tamb = 35ºC; 3.0m/s wind speed

HFcon = .169(Tcon) + 21 [W/m^2]@ Tamb = 35ºC; 3.0m/s wind speed

- An ideal transducer,

HFamb*Tamb = HFsk*Tsk

- For a more realistic model,

HFamb = (Tsk/Tamb) * HFsk * (1 + D)

D = sensor introduced deviance

- Overall system equation,

HFbc = (.312(Teva) + 25.2 + .169(Tcon) + 21 + .5833(Trad) + 30.96 – .312(Teva) + 25.2)·(Tsk/Tamb)·(1+.03)

- For our measuring device,

$V_{out} = HF * 125 \mu V \cdot W^{-1} \cdot m^2 \pm 3.0\%$

Results

Solving the equations, we arrive at the following results:

$HF_{eva} = -35.5\ W/m^2$;$HF_{rad} = 50.2\ W/m^2$; $HF_{con} = 26.6\ W/m^2$

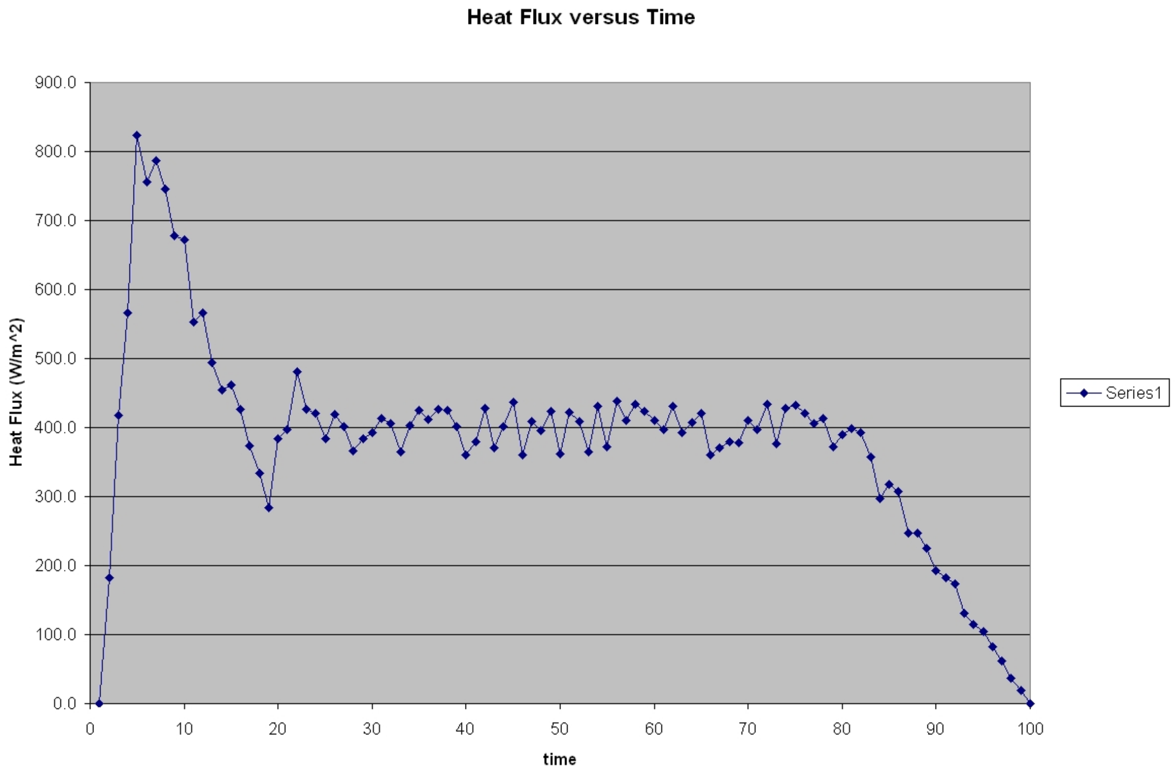
$HF_{bc} = 440\ W/m^2$

$V_{out} = 55 \pm 5.5\ mV$

This readout holds for when the ambient, heat production from work, and body thermoregulatory responses are in steady-state.

If we take the heat flux chart readout from a similar study, we see heat flux measurements from four different locations on the body, as well as characteristic response typical of an athlete in an aerobic exercise under constant environmental conditions.

Figure 2: Heat flux transducer chart recorder readout; W/m² with respect to time



This above data can be described in terms of several distinct periods,

- An initial period where the heat flux spikes to high value due to the onset of physical work and generation of heat.
- A dampening of heat flux as the body's thermoregulatory responses compensate for the increased heat flow (at which we see 50mV readout, correlating to 399.5 W/m² heat flux).
- Some variation in heat flux during a steady-state activity, that can be accounted for several factors detailed in the model, such as
- A change in ambient temperature or relative humidity
- A change in wind speed
- A change in level of exertion
- Changes in sensor functionality, such as contact w/ the skin
- As physical exertion is completed, the heat flux from body to ambient gradually decreases to zero as

For this type of exertion, prior to the onset of heat illness, one would expect to see a consistent, gradual decrease in heat flux as thermoregulatory

responses begin to decline (such as when the runner has expended their supply of body water for sweat, and no longer dissipate heat by sweat evaporation). It is at this point safety monitoring personnel should query the runner to gauge the onset of heat illness, and consider removing the athlete from the competition.

Changes in environmental conditions, such as temperature, humidity, and wind speed, can be accounted for by comparing changes in steady-state heat flux to characteristic equations for those components in the model.

Errors in the heat flux transducer can be shown to be small compared to the peak heat flux measured, and as such can be filtered from a change in heat flux evaluation used to predict heat illness.

Discussion

For discussion we can consider the model and heat flux transducer data in usage for various activities.

Anaerobic Athlete

Anaerobic athletes, such as the case of a football player, generate heat in short durations. The effects of this heat generation can be cumulative if periods of rest are not long enough to decrease body temperature, or if periods of exercise are long enough to exhaust reserves of body fluids. Environmental conditions are variably beneficial or antagonistic. Clothing and equipment can impede heat dissipation to the environment.

The initial spike in heat and post-activity cooling down should remain similar to the marathon runner, but the period of steady-state heat loss would likely not occur as thermoregulatory response interaction with ambient conditions would not have time to stabilize. Protective equipment should decrease the effect of heat transfer mechanisms.

The monitoring algorithm should likely key on the negative slew rate of the voltage readouts during the periods where heat is no longer being generated due to activity, but the thermoregulatory responses should still be dissipating stored heat.

Physical Labor in a Variable Environment

Some occupational tasks generate heat in short durations, but over extended periods of work. Examples include roofers, construction workers, or farmers. Antagonistic conditions are common. Clothing and safety equipment generally provide some impediment to heat dissipation.

Data from this activity would be similar to the anaerobic athlete, in that the periods of activity are of shorter duration. Heat transfer could be negative over extended periods of time as the ambient adds heat to the body rather sinks heat generated by work. The same negative slew rate is an indicator of effective body response to overheating.

Physical Labor in an Extreme Environment

Environmental conditions can extreme in occupations such as firefighters or other workers in high heat environments. Protective equipment is designed as a thermal insulator, which also serves to prevent the body from dissipating heat.

Data from this type of activity would expect to be quite different from previous cases, as antagonistic conditions overwhelm heat dissipation mechanisms. Integration of heat transfer over time may yield useful data in predicting critical overheating.

Significance

Human thresholds for the onset of heat stress illness are not fully defined. Experiments directly measuring body core temperature have shown the human body able to withstand temperatures in excess of the values typically associated with damage. As such there remains significant biomedical characterization necessary prior to any implementation of such a method.

Bond graph models have previously not been developed to show the total heat transfer system between the human body and various environmental contributors. Previous approaches to monitoring the body against heast stress risks have depended primarily upon temperature measurements and static thresholds to determine the onset of heat stress illness. The concept of monitoring changes in heat transfer to determine an unhealthy thermoregulatory response has previously not been introduced. The method presented in this paper is appropriate for further development and experimentation.